



Post-Flight EDL Entry Guidance Performance for the 2011 Mars Science Laboratory Mission

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Introduction



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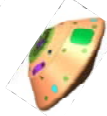
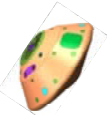
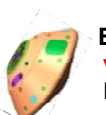
- Mars Science Laboratory landed Curiosity in Gale Crater on 5 Aug 2012
 - First Mars guided entry to a touchdown ellipse of 19×7 km, landing 2.2 km away from the expected target
- Entry guidance is derived from the Apollo capsule “final phase” logic and adjusts the range flown during entry by varying the direction of the lift vector (i.e., bank angle)
 - Flight proven algorithm with minor modifications
 - Algorithm consistently met ellipse size requirements and performance constraints since conceptual development in 2000



Guided Entry Phases



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Event Description & Nominal State	Phase	Guidance Actions
 Maneuver to Attitude Hold After Cruise Stage Separation Prior to EI-9 min  Entry Interface Occurs E+0 sec, h=126km, range=632 km, inertial vel=5845 m/s, inertial FPA=-15.47 deg	Pre-Bank	Attitude hold at a ground-commanded bank angle until Range Control Phase starts
 Begin Range Control Phase Filtered drag acceleration $\geq 0.2g$ E+51 sec, h=52km, range=350 km, M=29, relative vel=5839m/s  Peak Heating Occurs E+63 sec, h=39 km, range=283 km, M=24, v=5606 m/s, load=4g  Peak Loading Occurs Load = 12.5 g E+80 sec, h=23 km, range=200 km, M=19, v=4189 m/s	Range Control (Start of Guided Entry)	- Command bank angle magnitude to minimize predicted downrange error at deployment - Command bank reversals to manage crossrange error
 Begin Heading Alignment Phase v = 1100 m/s E+136 sec, h=14 km, range=83km, M=5, load=1.7g	Heading Alignment	Command bank angle to minimize residual crossrange & maximize deploy altitude
 Initiate Chute Deploy Sequence v = 406 m/s E+259 sec, h=12 km, range=5 km, M=1.7	Chute Sequence (End of Guided Entry)	Initiate sequence on velocity trigger to prepare for chute deploy

MSL Telemetry



Range Control Logic Overview



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- Apollo final phase controls to terminal range and velocity target using pre-derived influence coefficients with respect to errors about a nominal reference trajectory that ends at parachute deploy
- Reference trajectory defined by range-to-go, drag acceleration, and altitude rate as a function of relative velocity
- Commanded bank angle varies to control range based on deviations in predicted range, altitude rate, and drag from a reference trajectory

Predict Current Range:
$$R_p = R_{ref} + \frac{\partial R}{\partial D}(D - D_{ref}) + \frac{\partial R}{\partial \dot{r}}(\dot{r} - \dot{r}_{ref})$$

Find Commanded Vertical L/D Required to Converge Range to Target:
$$\left(\frac{L}{D}\right)_{v,c} = \left(\frac{L}{D}\right)_{v,ref} + \frac{K_3(R - R_p - R_{dep})}{\partial R / \partial (L/D)_v}$$

Bank Required For Commanded L/D:
$$\Phi_c = \cos^{-1}\left(\frac{(L/D)_c}{(L/D)}\right) \times K_2$$

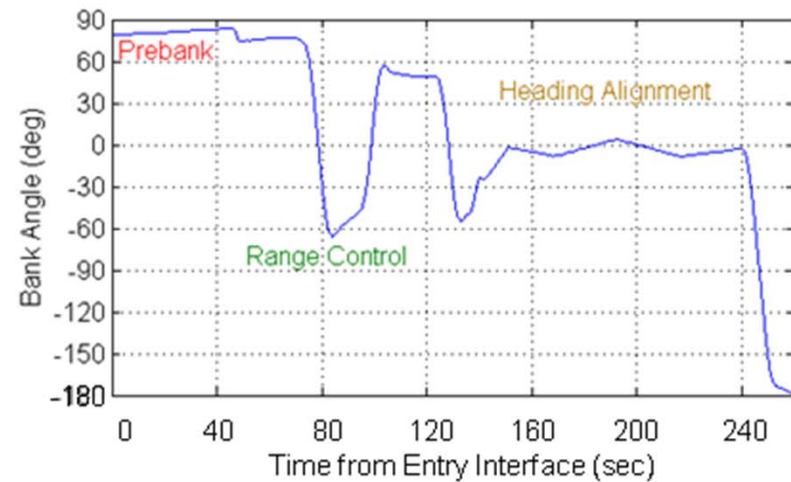
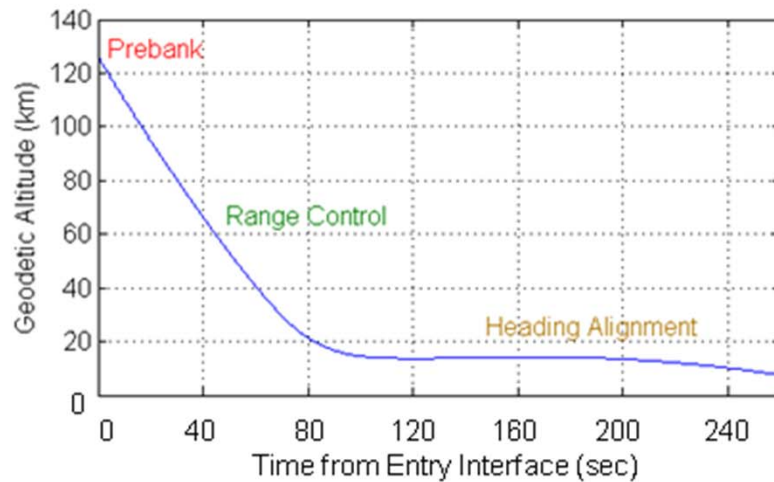
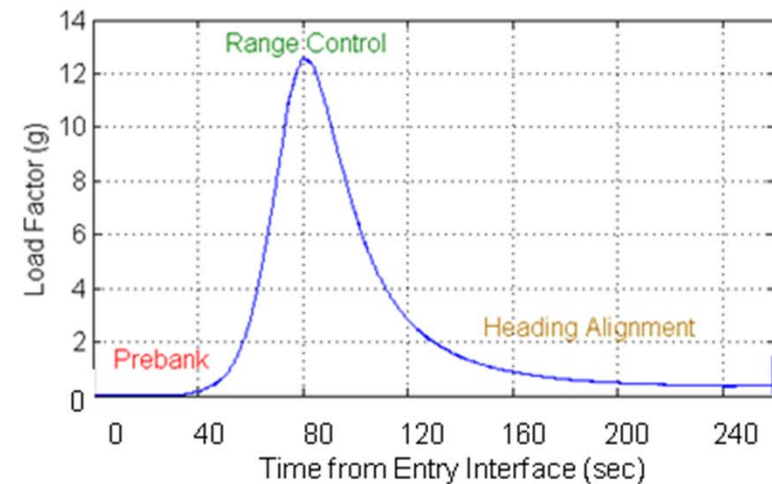
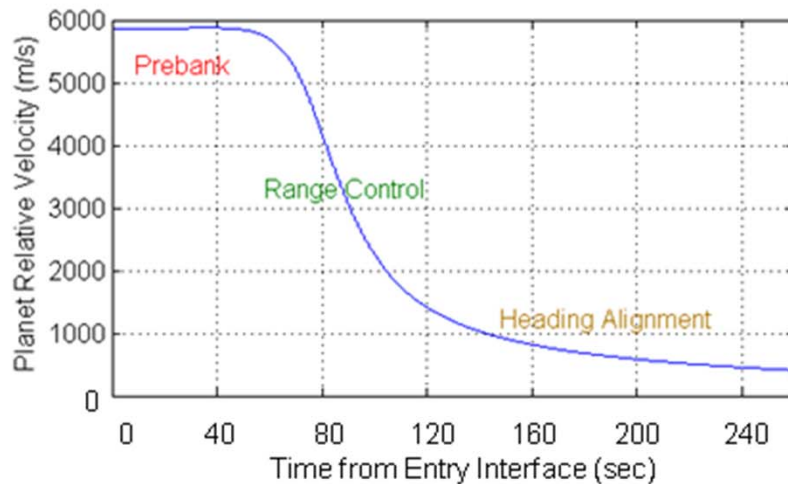
R	Range to Target
R _p	Range, predicted
R _{ref}	Range, reference
R _{dep}	Range, deploy bias
D	Drag
D _{ref}	Drag, reference
L	Lift
r	Altitude Rate
r _{ref}	Altitude Rate, ref
$\dot{K}_3$	L/D over-control gain
$\dot{K}_2$	Bank left/right control



MSL Reconstructed Entry Trajectory



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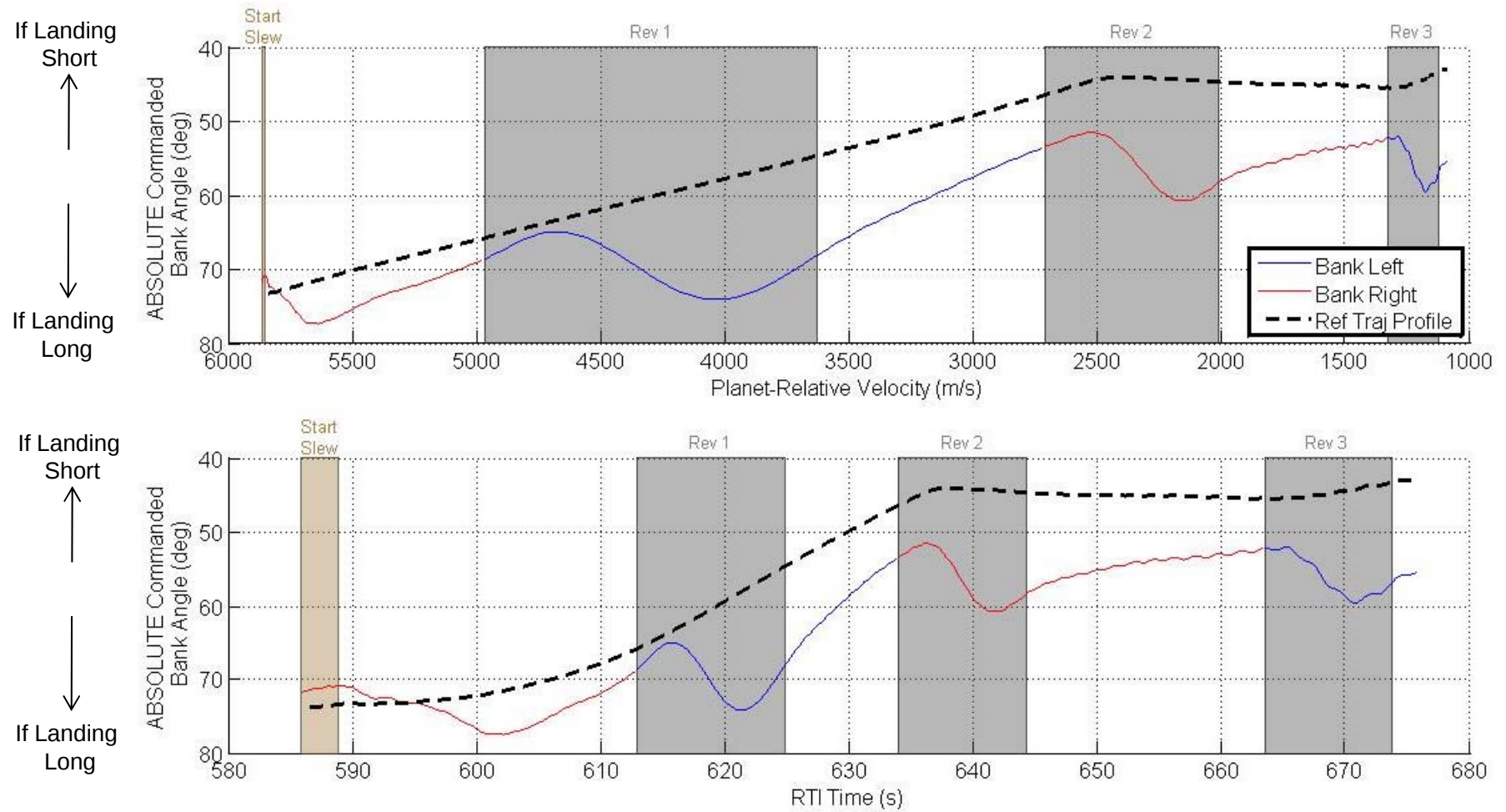




Commanded Bank Angle Telemetry



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Range Error Components Telemetry



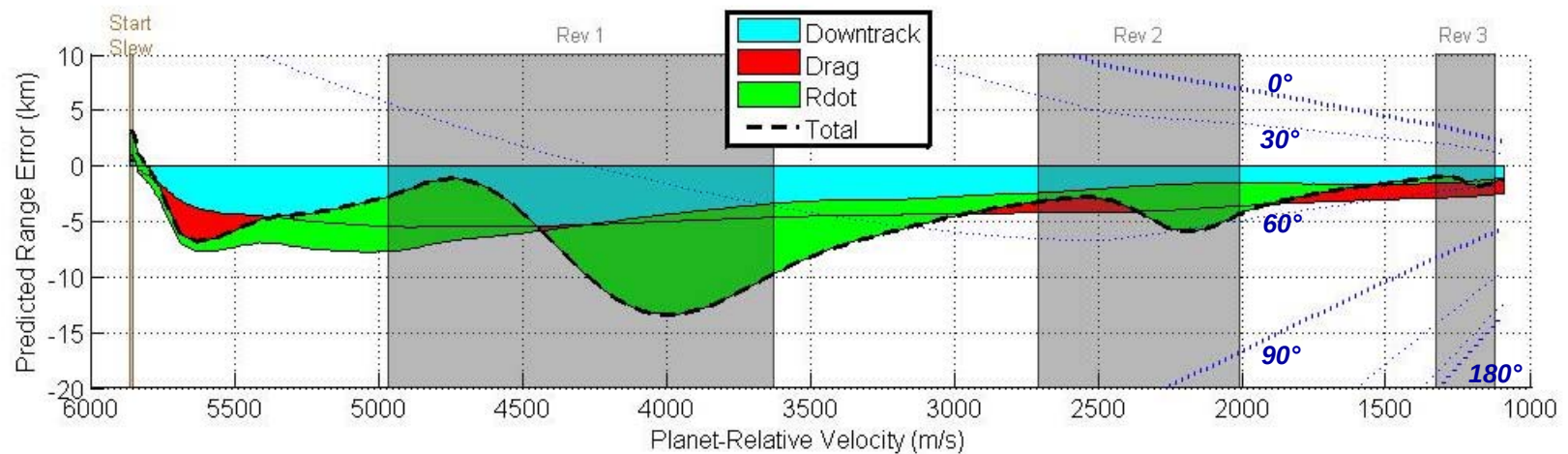
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$$R_{error} = (R - R_{ref} - R_{dep}) - \frac{\partial R}{\partial D}(D - D_{ref}) - \frac{\partial R}{\partial \dot{r}}(\dot{r} - \dot{r}_{ref})$$

If Landing
Short



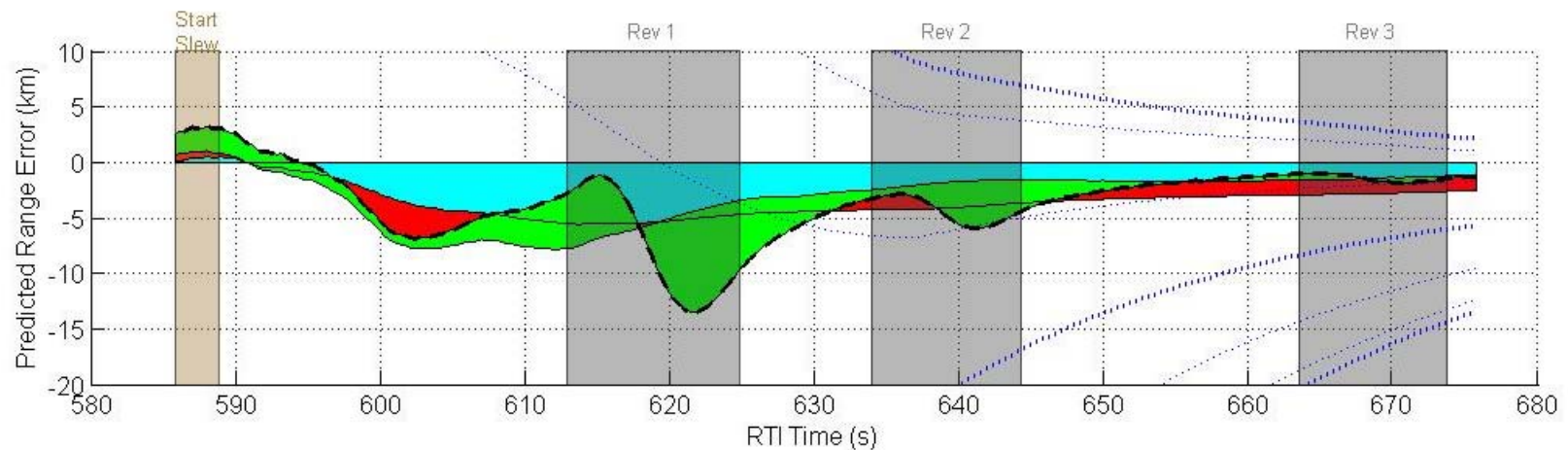
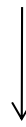
If Landing
Long



If Landing
Short



If Landing
Long

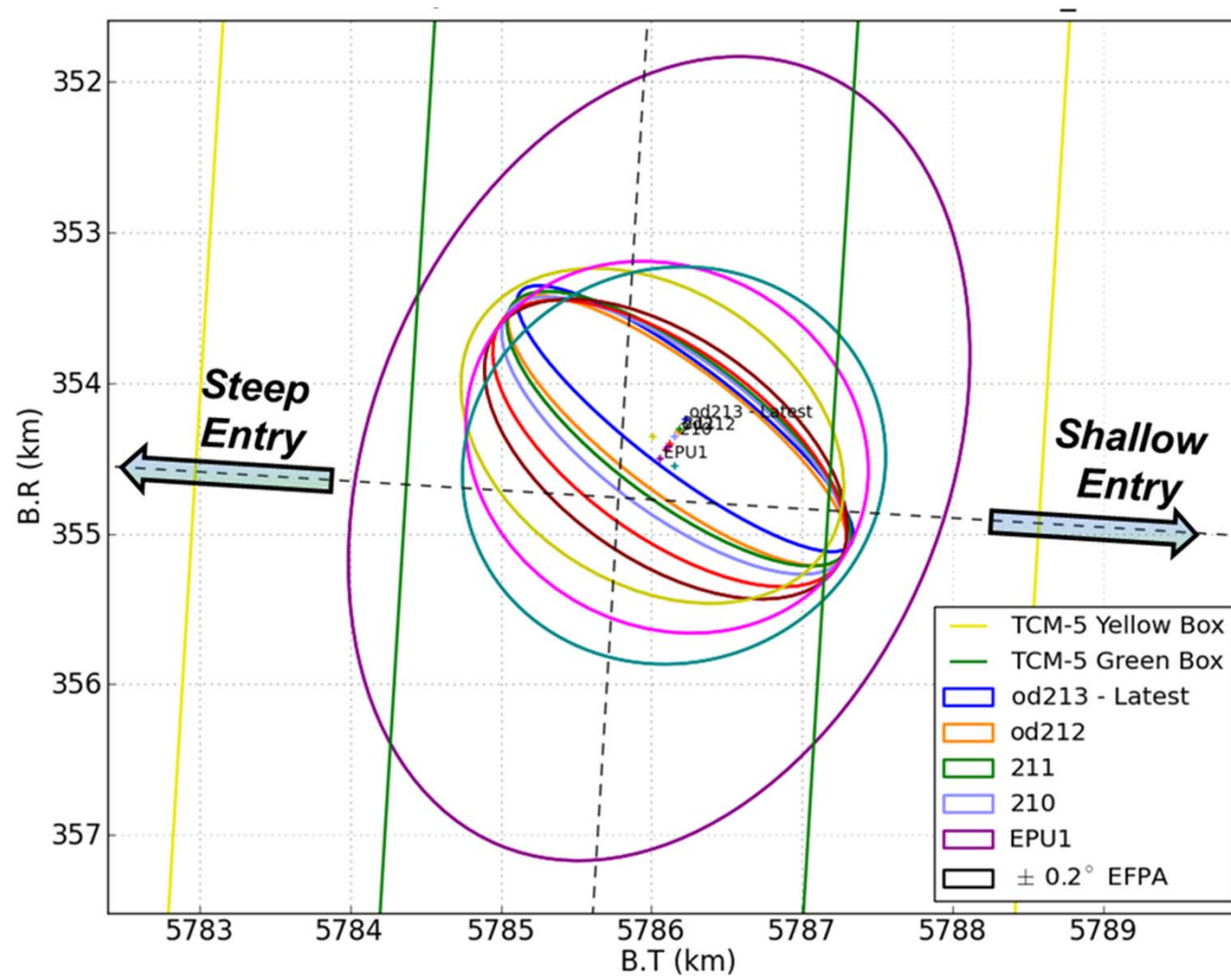




Delivery Uncertainties from Entry -8 to -1 days



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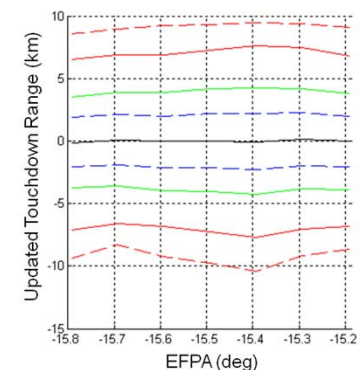
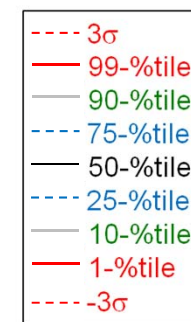
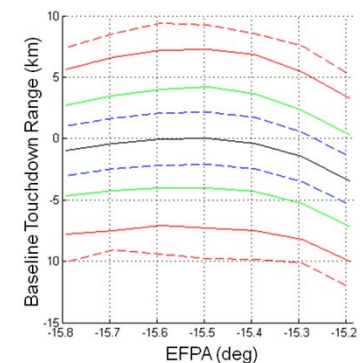
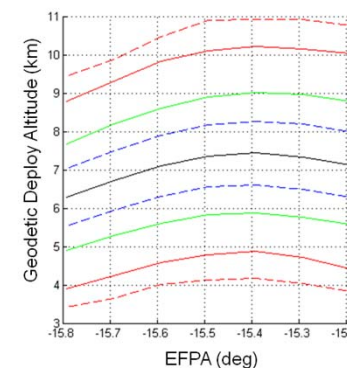
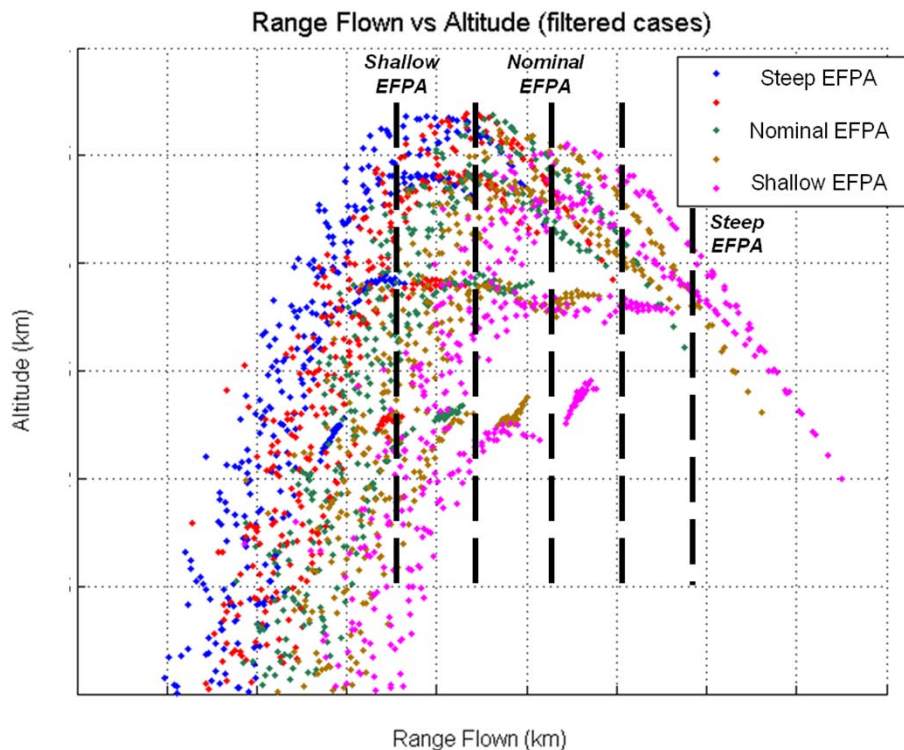


Operations Planning for Delivery Errors



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- For a given atmospheric entry point, what guidance reference trajectory will perform well to reach the intended landing site?
- Evaluated thousands of combinations before settling on a small number of different guidance gain sets to be chosen via the predicted entry flight path angle (EFPA)





Contributions to Landing Site Error

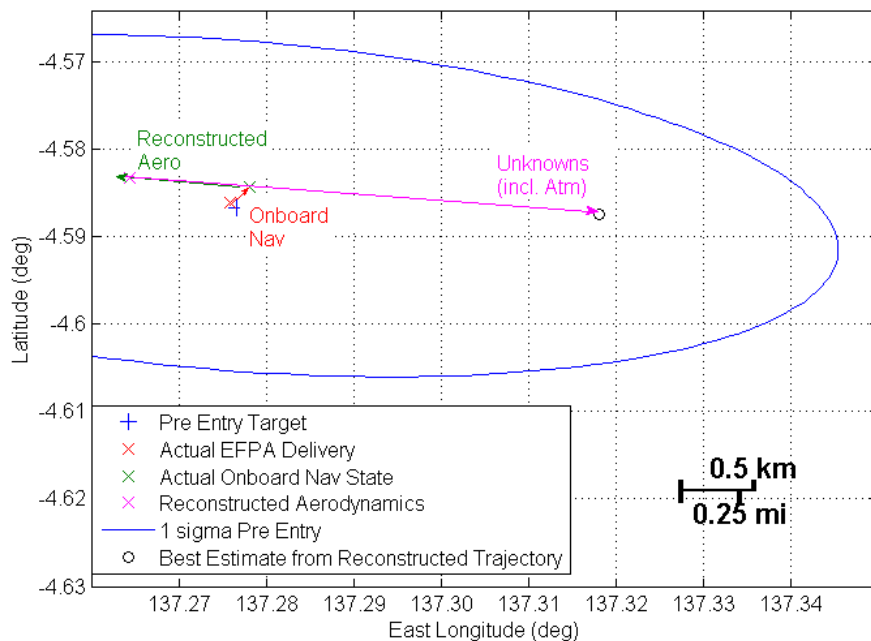


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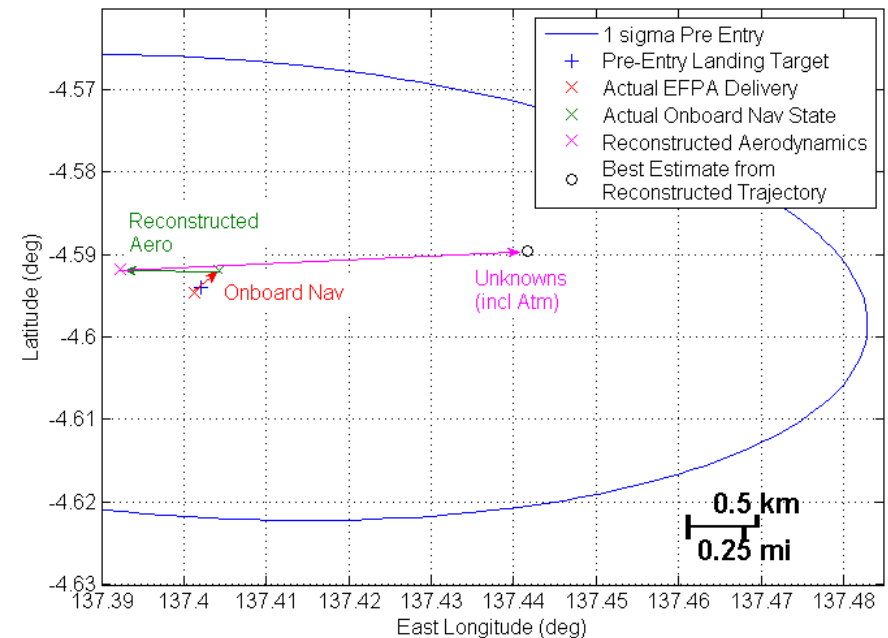
Source Data	Guidance Prediction, Relative (km)	Delta (km)	Downrange at Deploy, Relative (km)	Delta (km)	Downrange at Landing, Relative (km)	Delta (km)
Monte Carlo of Pre Entry Trajectory	0.0	--	0.0	--	0.0	--
+ Actual EFPA Delivery	0.0	0.0	0.0	0.0	0.0	0.0
+ Actual Onboard Nav State	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2
+ Reconstructed Aerodynamics	0.5	0.5	0.7	0.8	0.6	0.7
Best Estimate from Reconstructed Trajectory	-0.6	-1.0	-2.4	-3.1	-2.3	-2.9

Negative values are downrange past the target

Parachute Deploy



Touchdown





Summary & Forward Work



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- Curiosity landed successfully only 2.2 km away from the expected target given the onboard navigation state
 - Better than the average Apollo capsule splashdown miss distance
 - A late bank reversal and a suspected tail wind contributed to this slight miss
- Refinement of the guidance gains and alternative parachute deploy triggers to reduce the ellipse size will be studied for future Mars landing missions